Workshop on Critical Point and Onset of Deconfinement -2022

Results from STAR BES

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STAR

IISER BERHAMPUR

In part supported by

U.S. DEPARTMENT OF ENERGY

Office of Science

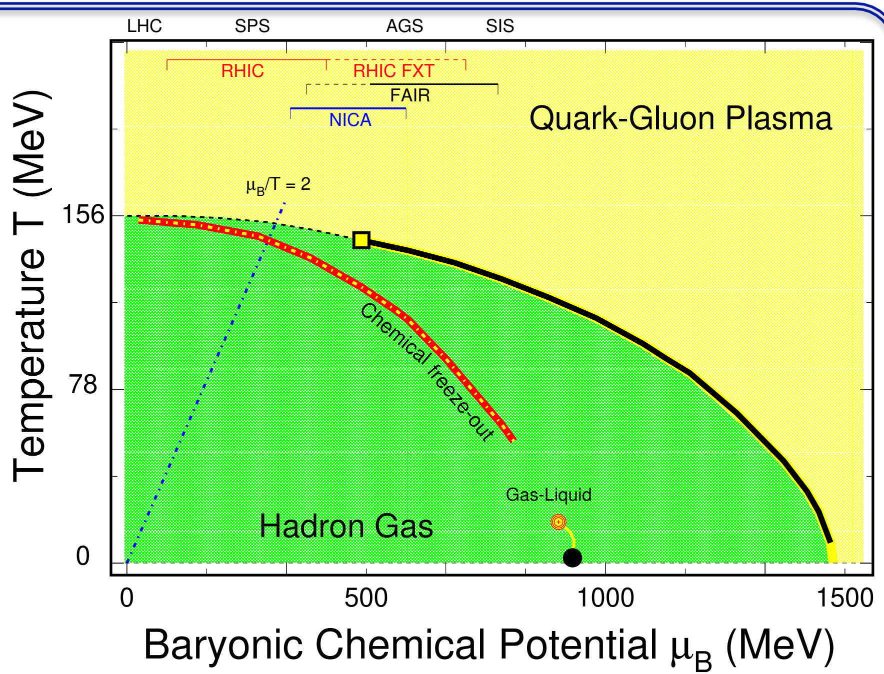
Motivation

Probing the QCD matter:

- Strangeness production at high μ_B
- Hadronic re-scattering
- Spin polarization
- Hyperon-nucleon interaction

Mapping the QCD phase diagram:

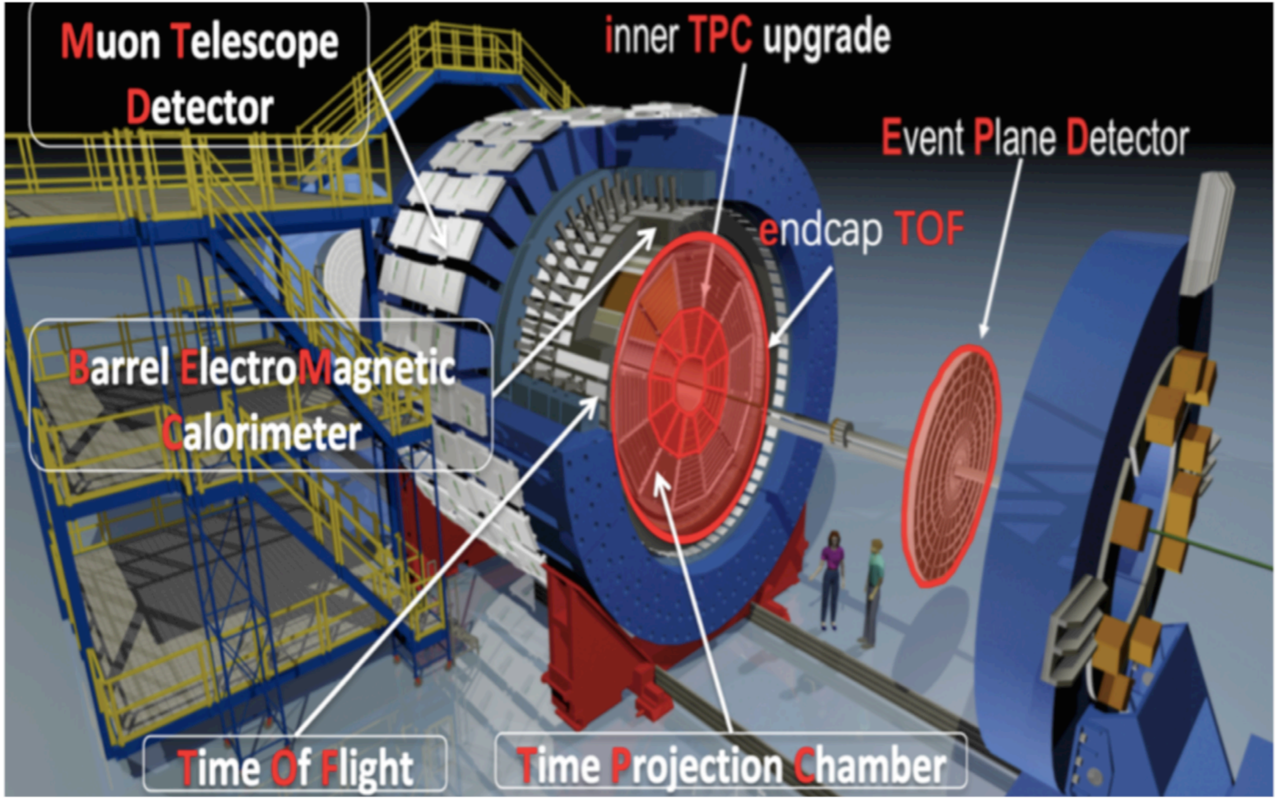
- Phase-boundary
- Critical point
- Onset of de-confinement
- Signature of 1st-order phase transition



Varying beam energy varies Temperature (T) and Baryon Chemical Potential (μ_B).

B. Mohanty, N. Xu, arXiv:2101.09210

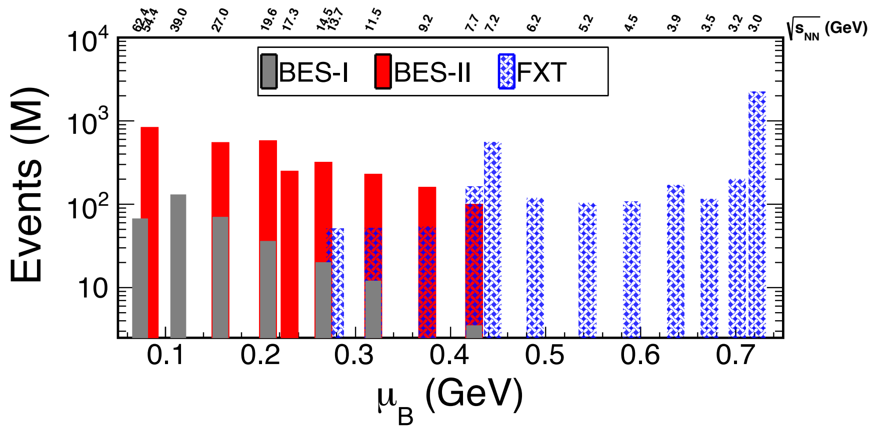
The STAR Experiment

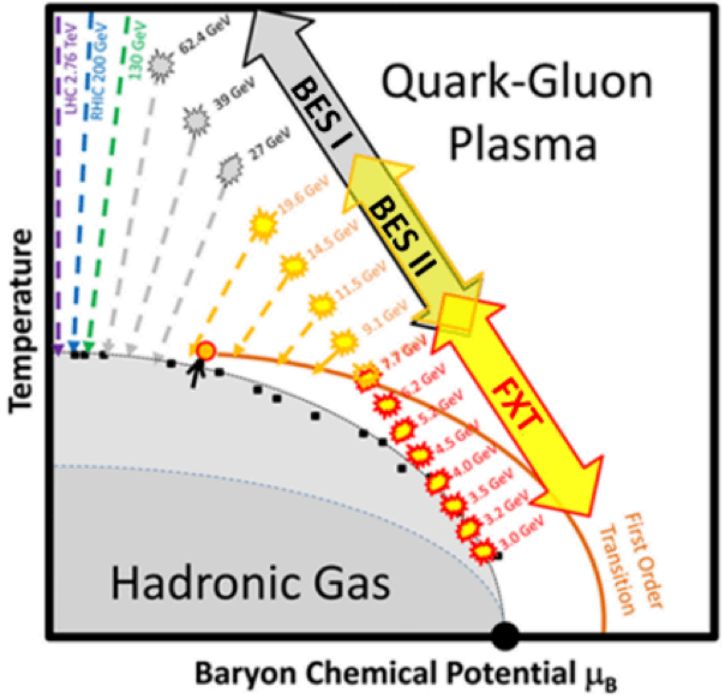


- Detector upgrades: iTPC, eTOF, EPD
- Tracking: TPC ($|\eta| < 1.5$)
- PID: TPC and ToF($|\eta| < 0.9$)
- Full azimuthal coverage

Beam Energy Scan Phase-II

Data taking for phase−II of BES was completed in 2021.





Data collected by STAR covers μ_B from 20-800 MeV

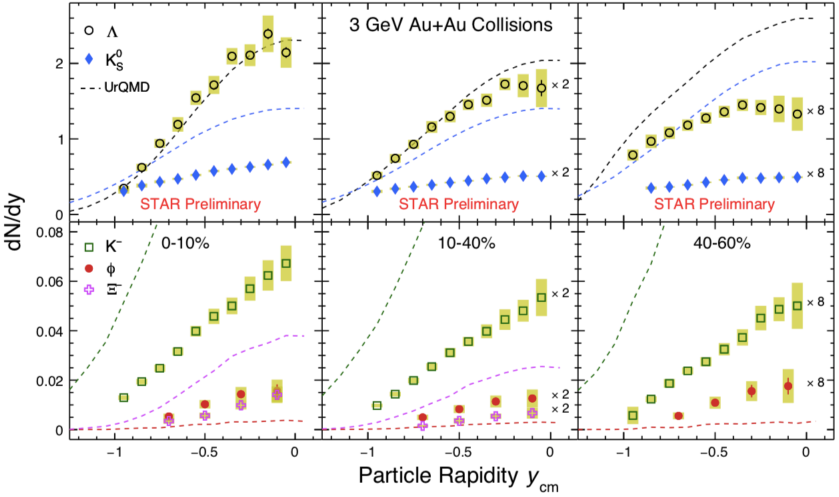
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Probing the QCD matter

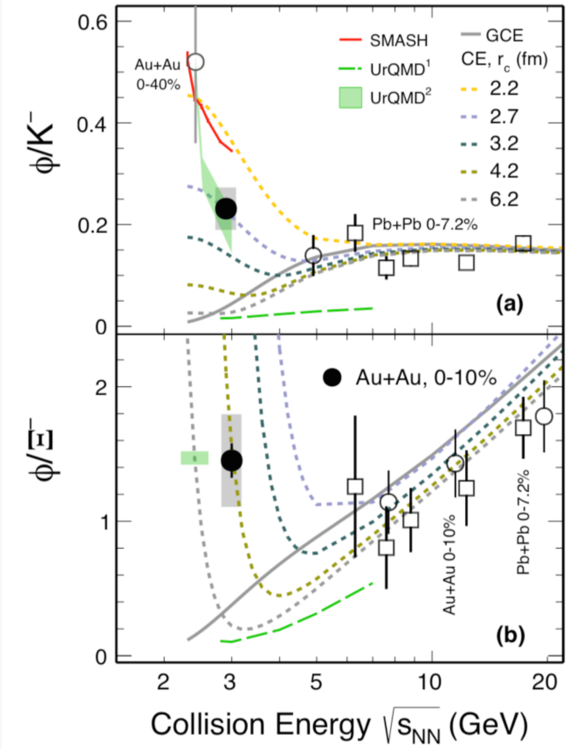
- Strangeness production & hadronic re-scattering
- Spin polarization
- Hyperon-nucleon interaction

Strangeness Production at 3 GeV

The strange hadron yield and ratios are sensitive to the strangeness production mechanism.



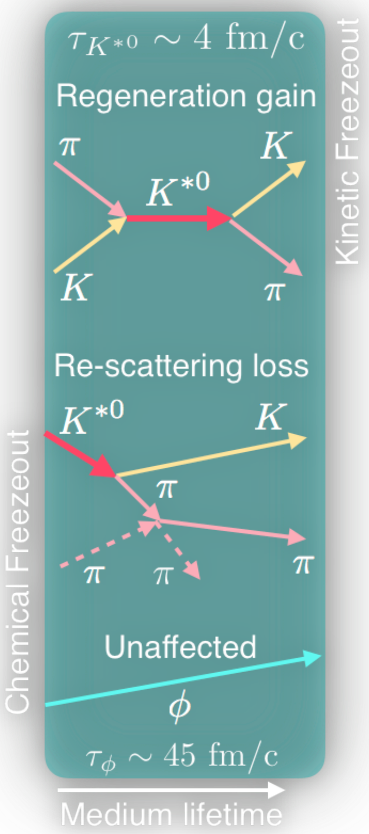
STAR: Phys. Lett. B 831 (2022) 137152



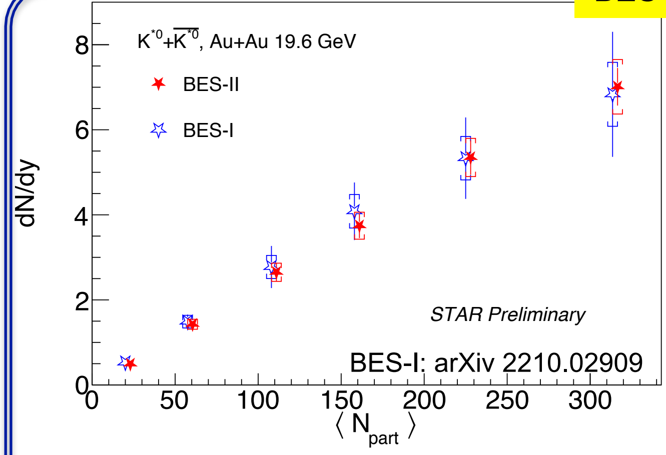
- Strange hadrons yields are measured in a wide rapidity range

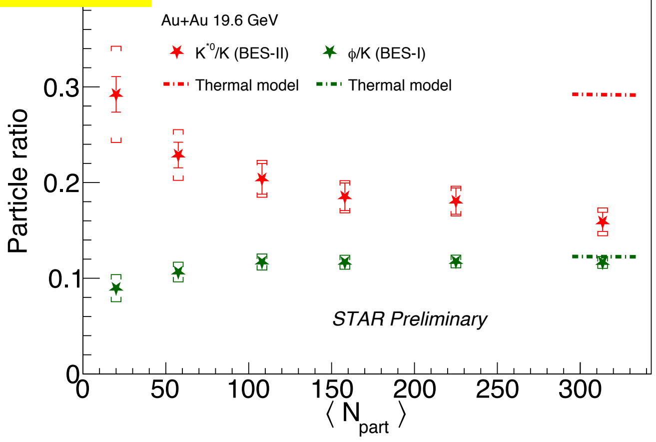
→ Data favor the Canonical Ensemble at high baryon density

Effect of Hadronic Re-scattering



BES-II, 19.6 GeV





Factor 3-4 reduction in statistical uncertainties @ 19.6 GeV (BES-II)

- $(K^{*0}/K)_{central} < (K^{*0}/K)_{peripheral}$
- ϕ/K : independent of centrality

Dominance of hadronic re-scattering in central Au+Au collisions

A. K. Sahoo
Tue, 29/11

Probing the QCD matter

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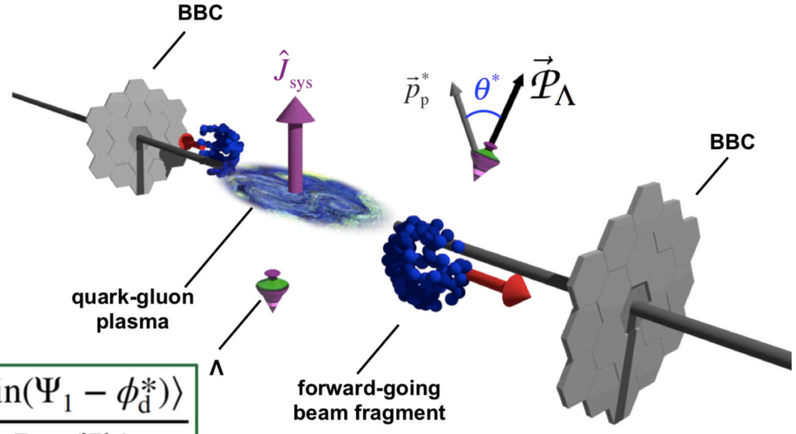
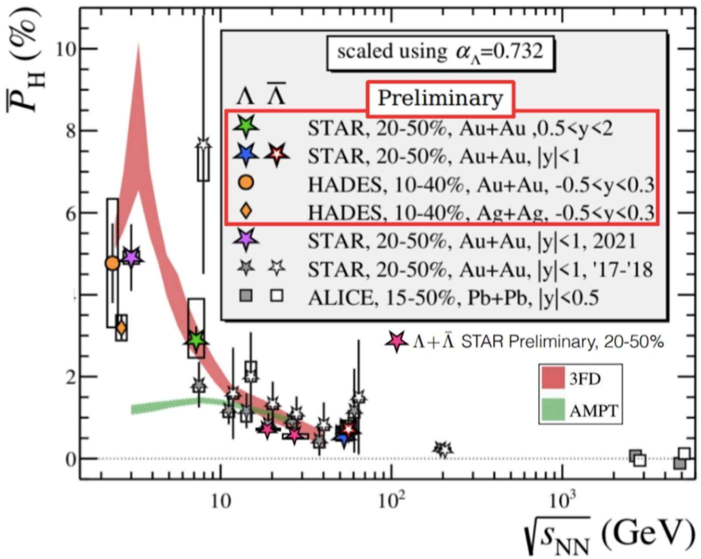
- Spin polarization
- Hyperon-nucleon interaction

Global Hyperon Polarization



$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$



- Probe for initial angular momentum and magnetic field
- Increasing global polarization with decreasing energy

Precision measurements using BES-II data follow the global trend

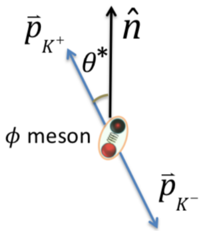
BES-II Results:
3, 7.2, 19.6, 27 GeV

D. Kharzeev, Nucl Phys A 803, 227 (2008), F. Becattini, et. al., Phys Rev. C. 77, 024906 (2008)

Global Spin Alignment of Vector Mesons

$$\frac{dN}{d(\cos\theta^*)} = A \times [(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

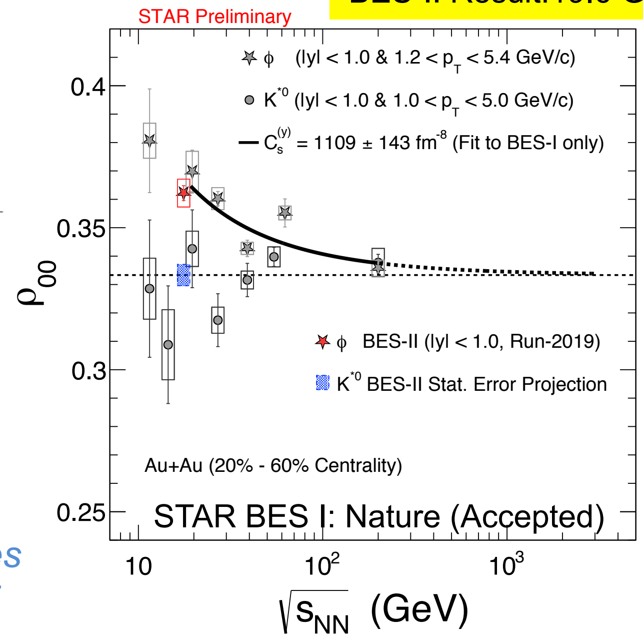
θ^* is the angle between the daughter momentum (rest frame) & vector perpendicular to event plane



ρ_{00} = 1/3 , no spin alignment

Au+Au, 19.6 GeV (BES-II) : ρ_{00} for ϕ > 1/3 (5.3σ)

BES-II Result:19.6 GeV



Vorticity tensor ~10^{-4}

Vector meson strong force field

$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

Quark coalescence vorticity & magnetic field ~10^{-5}

Electric field ~10^{-5}

Model with strong vector meson force field provides a possible explanation of measured values of ρ_{00}

K. Schiling et. al., Nucl. Phys. B 15 (1970) 397,
Z. Liang et. al., Phys. Lett. B629, 20 (2005),
X-L. Sheng et al., Phys. Rev. D 101, 096005 (2020),
Y. Yang et. al., Phys. Rev. C 97, 034917 (2018)

Probing the QCD matter

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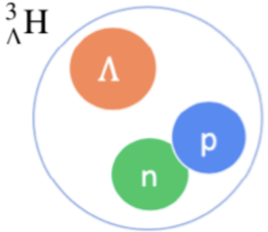
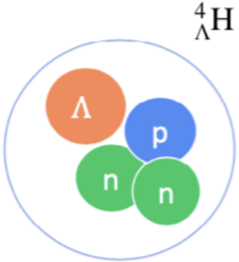
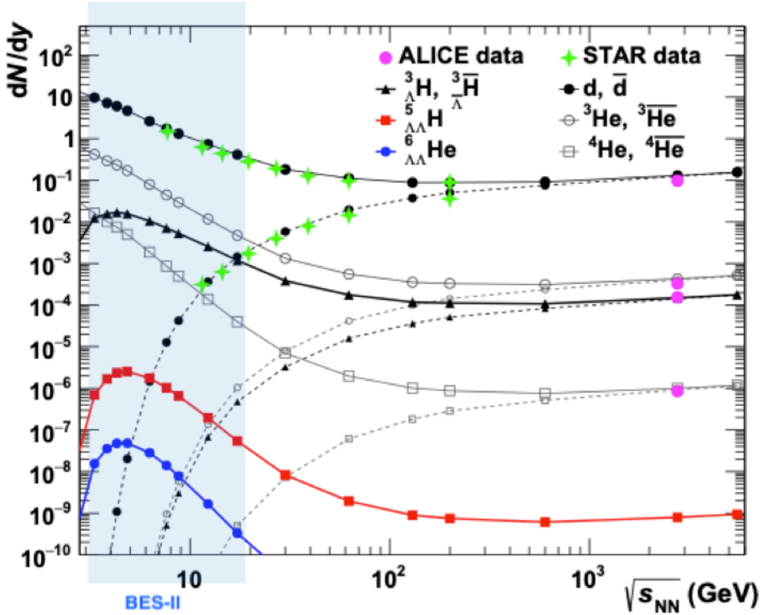
- Spin polarization
- Hyperon-nucleon interaction

Hyper-nuclei

- Bound system of nucleon and hyperon
- Probe for hyperon-nucleon interaction



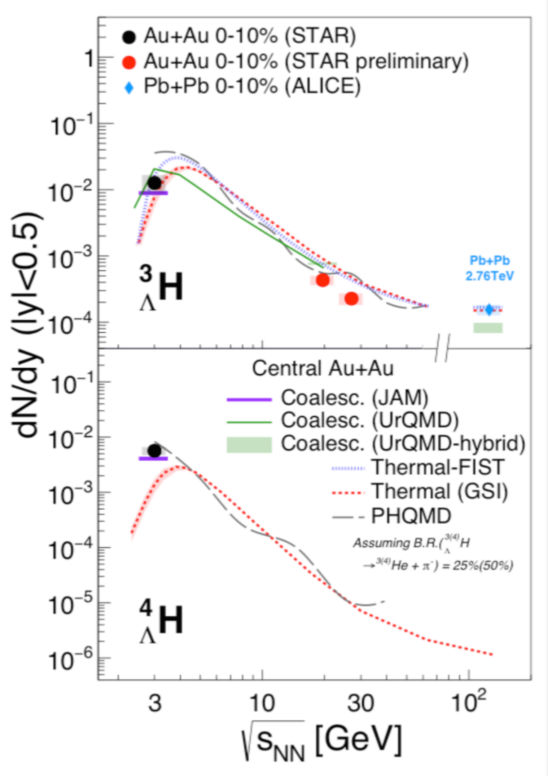




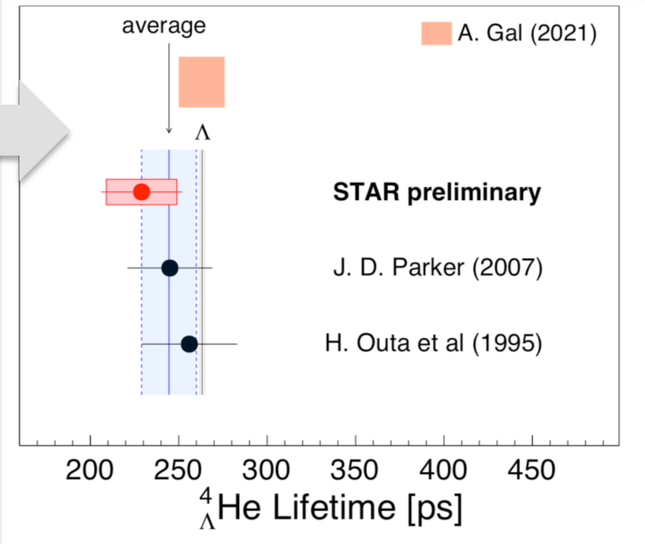
B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207

BES-II data provide a great opportunity to study hyper-nuclei production in heavy-ion collisions

Hyper-nuclei Yield and Lifetime



The first Hyper-Helium-4 lifetime measurement in heavy ion collisions



Energy dependence of hyper-nuclei production yields.

- Model calculations (Thermal, Coalescences) reproduce the energy dependence trend of measured yield.

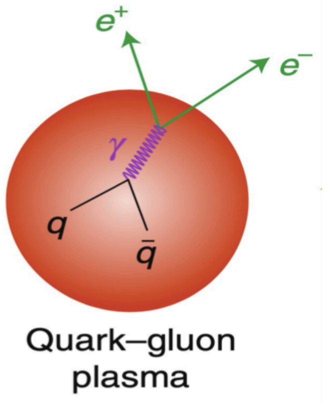
Provides constraints on Hyperon-Nucleon (Y-N) interactions

X. Li, Tue, 29/11

Mapping the QCD phase diagram

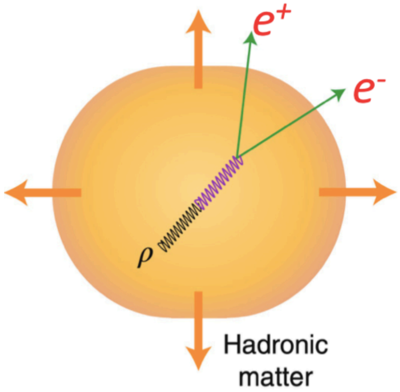
- Phase-boundary
- Critical point and 1st order phase transition
- Onset of de-confinement

Medium Temperature with Dileptons



Courtesy of Ralf Rapp

STAR: PRL 92, 092301 (2004), Rapp: PLB 753 (2016) 586



Contributions to dielectron mass spectrum from both QGP radiation and ρ decays

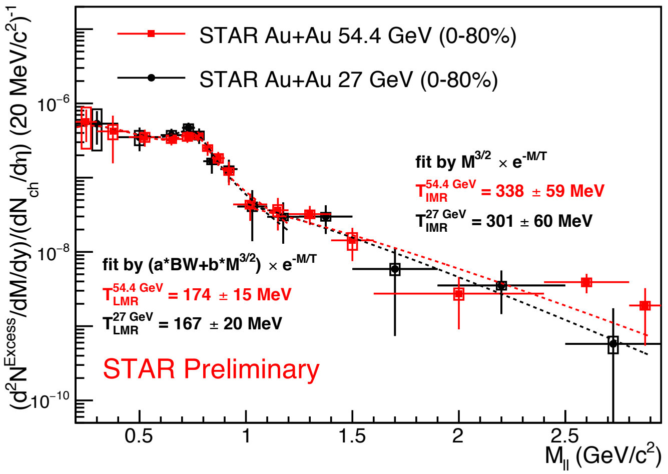
LMR : dominated by ρ mediated dielectrons

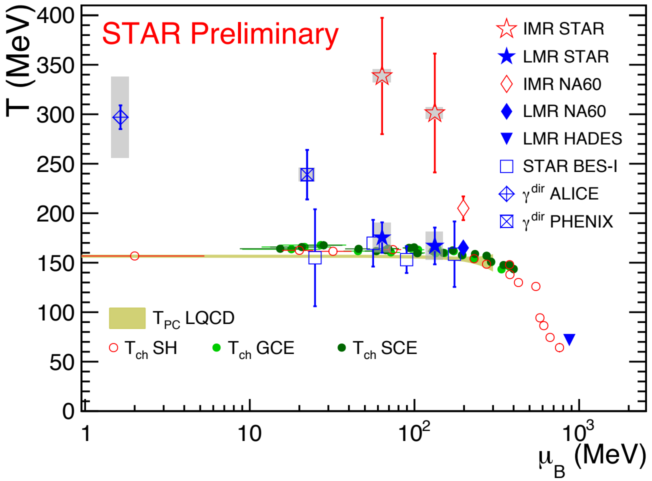
IMR : dominated by QGP radiation

Unlike photons, the measured temperature from the dielectron invariant mass spectrum is not affected by the blue-shift effect

Medium Temperature with Dileptons

Precision measurement of dielectron mass spectra at 27 and 54.4 GeV





LMR : Extracted medium temperature ~ Chemical freeze-out temperature

IMR : Extracted QGP medium temperature ~ 300 MeV

Mapping the QCD phase diagram

- Phase-boundary
- Critical point and 1st order phase transition
- Onset of de-confinement

Net-proton Fluctuation

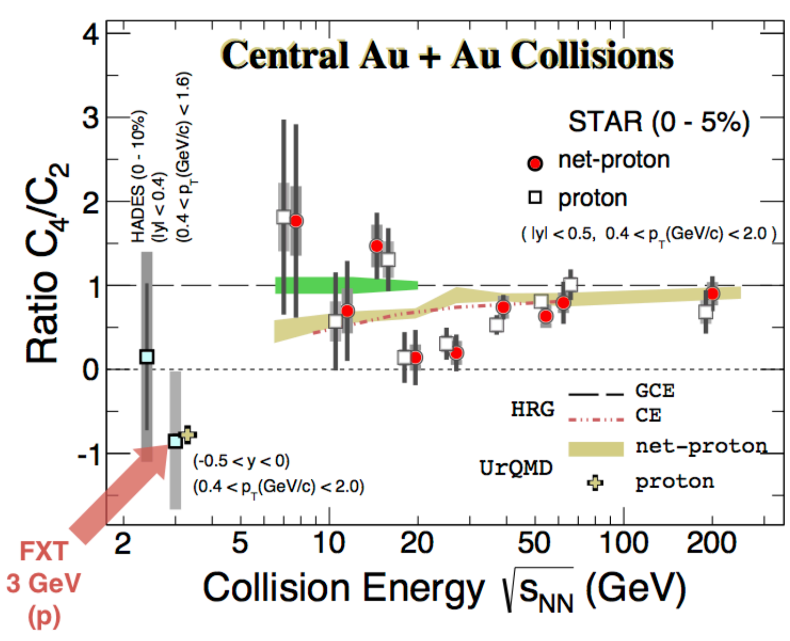
At critical point:

- Correlation length diverges
- Distributions are non-Gaussian

○ Au+Au $\sqrt{s_{NN}}$ = 7.7- 39 GeV
Hints of non-monotonic dependence of C_4/C_2 vs $\sqrt{s_{NN}}$

○ Au+Au $\sqrt{s_{NN}}$ = 3 GeV :
measured C_4/C_2 consistent with UrQMD

STAR: PRL, 126, 092301 (2021), PRC,104, 024902 (2021)



BES-II Result: 3 GeV

Nuclei Ratio vs Energy

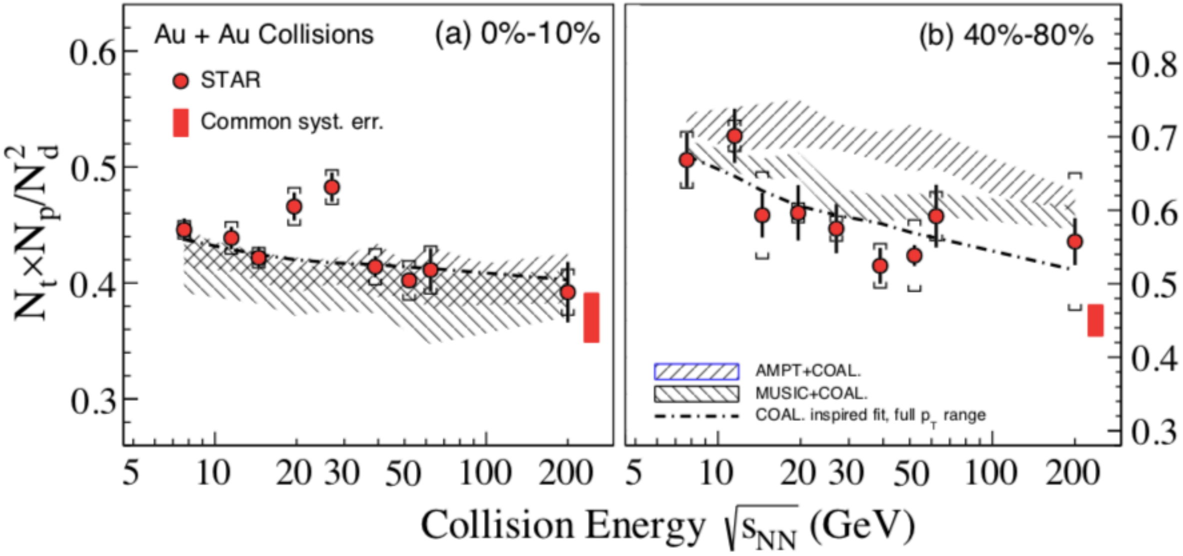
The ratio $N_t \times N_p / N_d^2$ is sensitive to the local density fluctuation of neutrons

- signature of 1st order phase transition and/or critical point

D. Zhang Thu, 01/12

0-10% centrality:
The non-monotonic energy dependence

40-80% centrality:
The monotonic energy dependence



K.-J. Sun, et al Phys. Lett. B 781, 499 (2018); E. Shuryak et al, Phys. Rev. C 101, 034914 (2020),

STAR: arXiv 2209.08058

Nuclei Ratio vs Energy

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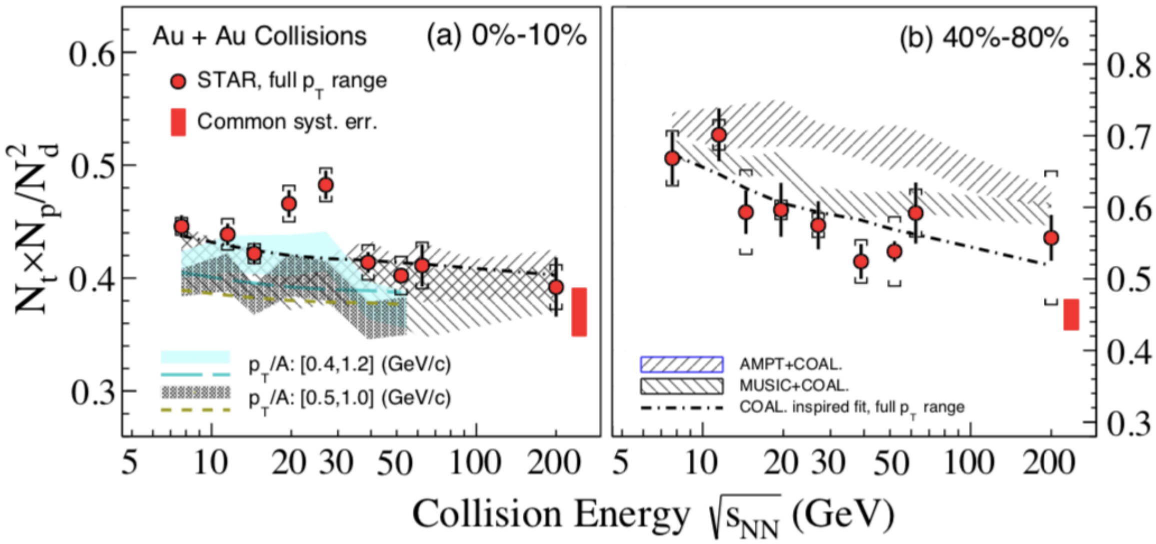
- signature of 1st order phase transition and/or critical point

The **ratio** $N_t \times N_p/N_d^2$ shows a transverse momentum acceptance dependence

Further theoretical input needed to make conclusion about the observed enhancement

D. Zhang Thu, 01/12



Mapping the QCD phase diagram

- Phase-boundary
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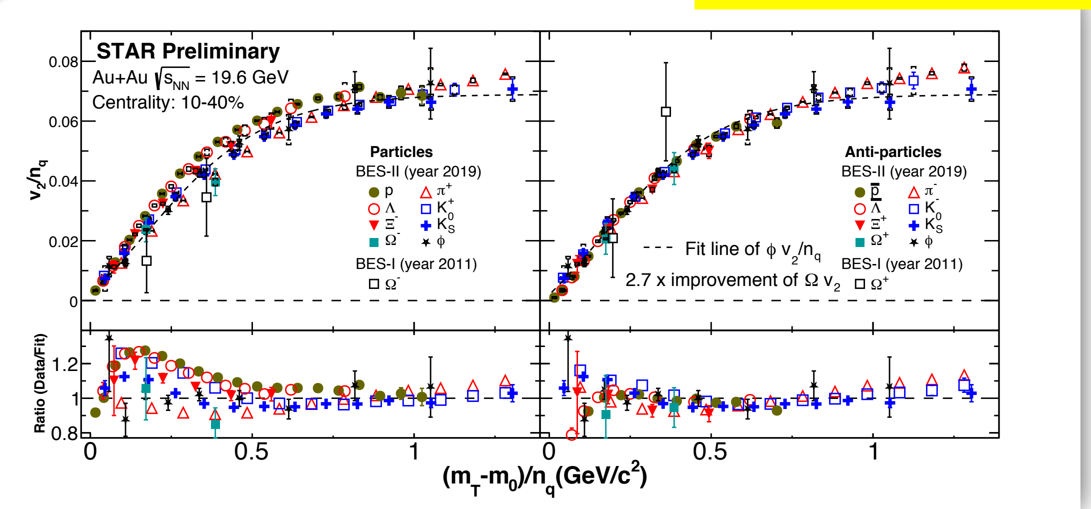
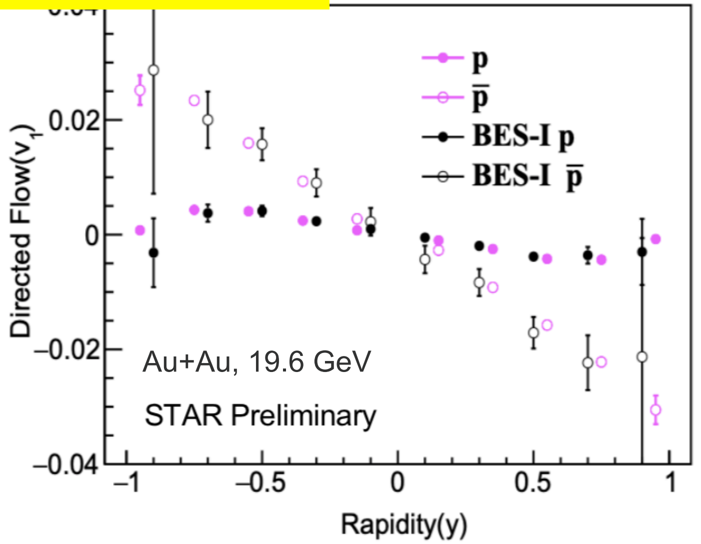
Collectivity Measurements from BES

BES-II Results: 14.6, 19.6 GeV





- NCQ-scaling holds for particles (~20%)
- ϕ meson v_2 follows NCQ scaling

-Signature of partonic collectivity

P. Dixit & S. Zhou
Wed, 30/11

Factor 2.5-4 reduction in statistical uncertainties @ 19.6 GeV (BES-II)

- Different v_1 slopes of p and p-bar *(transport quark effect)*

Collectivity Measurements from BES

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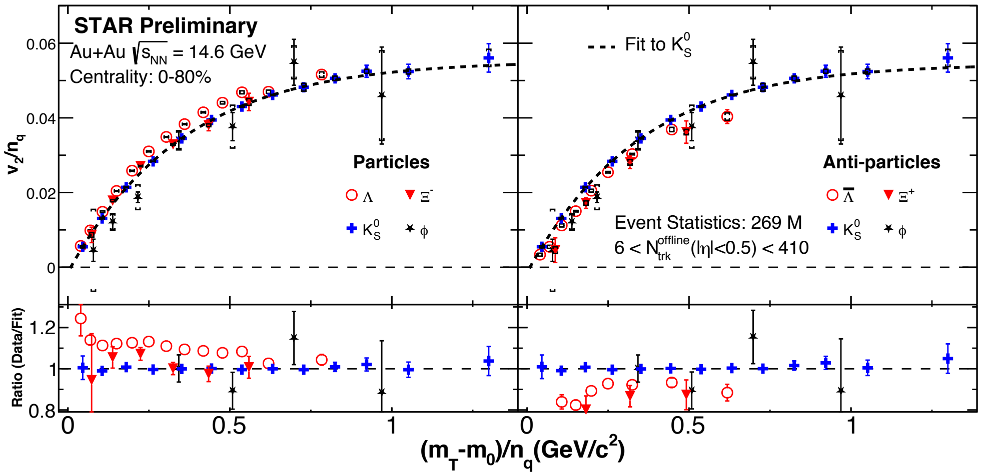

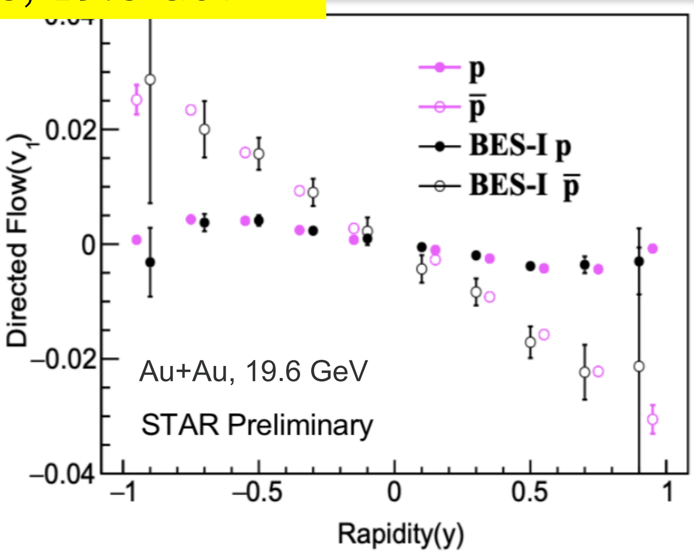

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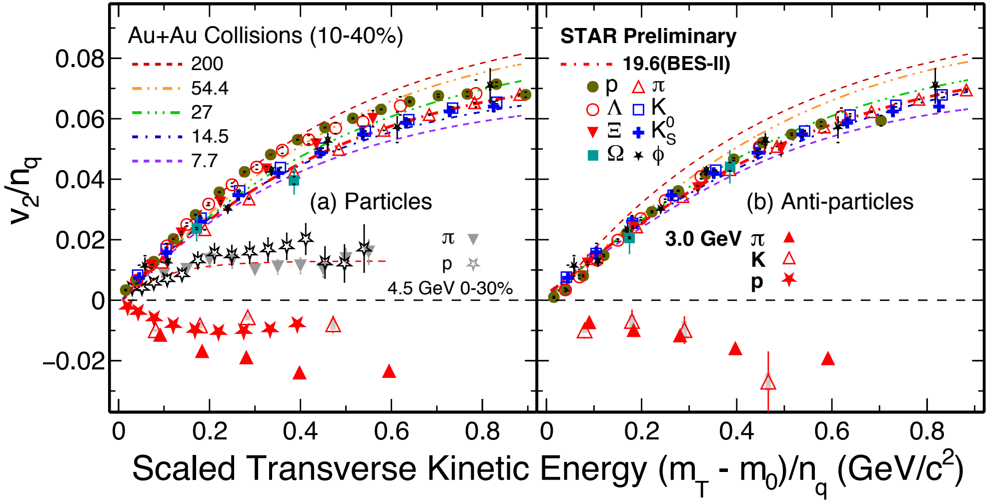
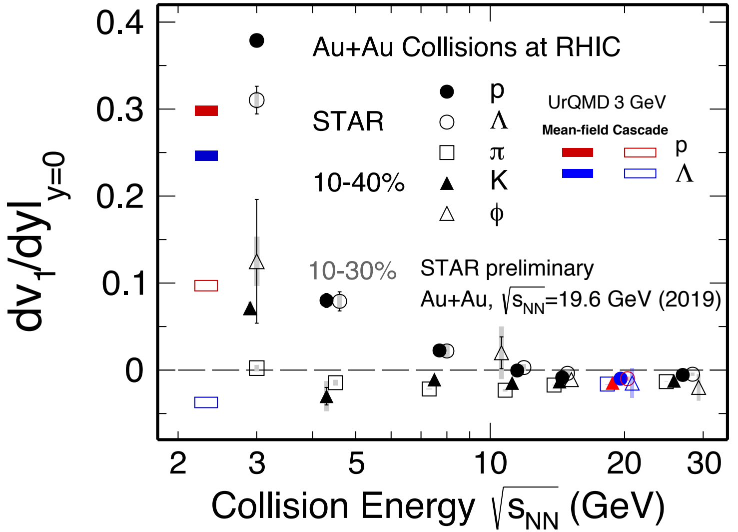


STAR: Phys. Lett. B **827** (2022) 137003

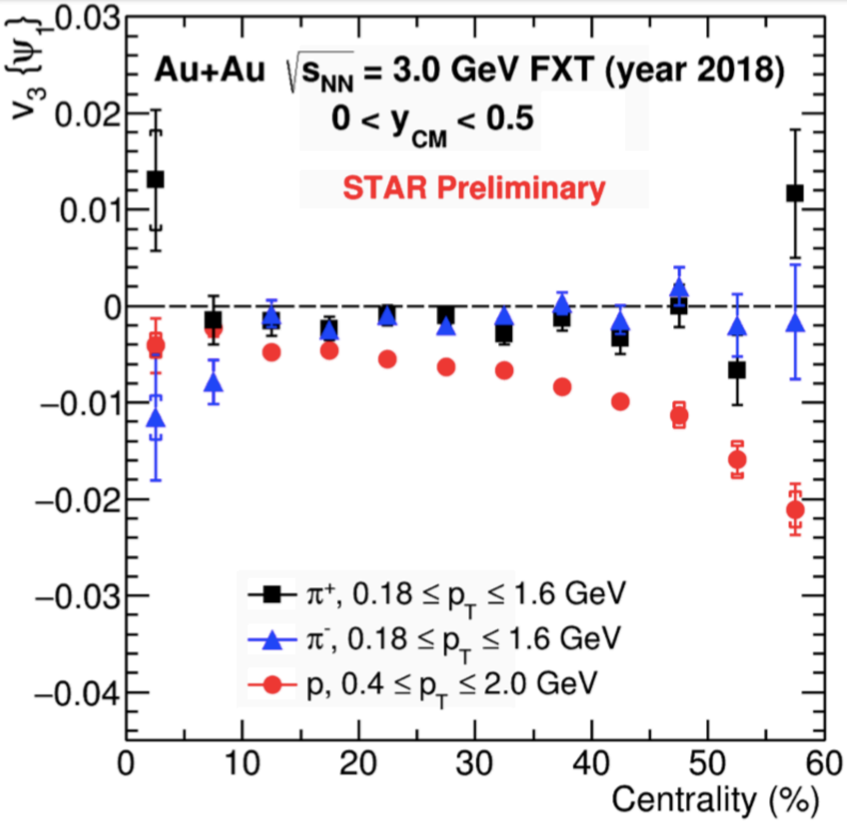
- No Number-of-Constituent-Quark scaling at 3 GeV

  -Disappearance of partonic collectivity



- UrQMD with **baryonic mean-field potential** qualitatively consistent with data at 3 GeV

Collectivity Measurements from BES



BES-II Results: 3 GeV

- Proton v_3 is correlated with ψ_1
- We expect $v_3(\psi_1)$ ~ 0 due to event-by event fluctuations
- Non-zero $v_3(\psi_1)$ may come from initial geometry related to baryon stopping

C. Racz, Wed, 30/11

Summary

- Au+Au $\sqrt{s_{NN}}$ =14.6 and 19.6 GeV (BES-II)
  - Precision measurements compared to BES-I
  - Signatures of deconfined quark matter are observed
- Au+Au $\sqrt{s_{NN}}$ = 3 GeV (BES-II, FXT)
  - Medium likely dominated by hadronic interactions

Our searches for the QCD critical point and 1st order phase transition continue.

Stay tuned for more BES-II results

List of STAR talks

1. *Probing the hadronic phase via the measurement of resonances in Au+Au collisions at $\sqrt{s_{NN}}$= 19.6 GeV from STAR BES-II –* ***A. K. Sahoo***

2. *Measurements of light hypernuclei production and properties in Au+Au collisions from STAR experiment –* ***X. Li***

3. *Elliptic flow of identified particles in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 GeV in BESII –* ***S. Zhou***

4. Reaction Plane Correlated Triangular Flow in Au+Au Collisions at \sqrt{s_{NN}} = 3.0 GeV from STAR – **C. Racz**

5. *Azimuthal anisotropic flow of identified hadrons in Au+Au collisions in BES-II energies –* ***P. Dixit***

6. *Beam Energy Dependence of Triton Production and Yield Ratio (Nt Np/Nd^2) in Au+Au Collisions at RHIC-* ***D. Zhang***

7. *Measurements of Local Parton Density Fluctuations via Proton Clustering from STAR Beam Energy Scan –* ***D. Neff***

Thanks…

Back-Up

Global Spin Alignment of Vector Mesons

Contributions to φ-meson ρ_{00} from theory

Physics Mechanism	ρ_{00}	
Electric field[1]	< 1/3	~10^{-5}
Electric part of vorticity tensor[1]	< 1/3	~10^{-4}
Fragmentation of polarized quarks[2]	≳ 1/3	~10^{-5}
Magnetic components of EM and vorticity fields[1,2,3]	< 1/3	~10^{-5}
Helicity polarization[4]	< 1/3	
Locally fluctuating axial charge currents[5]	< 1/3	
Local vorticity loop + coalescence[6]	< 1/3	
Vector meson strong force field[1,7]	> 1/3	

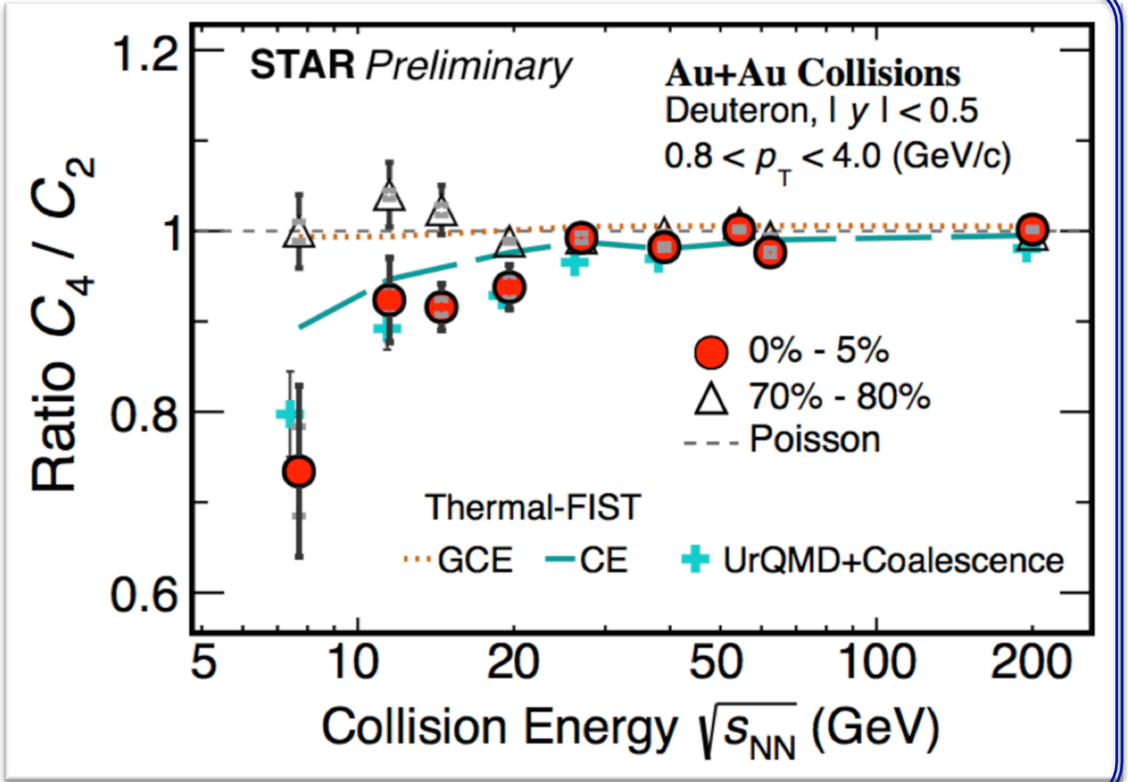
Gavin Wilks SQM2022,

[1] Sheng et al., Phys. Rev. D 101, 096005 (2020).
[2] Liang et al., Phys. Lett. B 629, 20–26 (2005).
[3] Yang et al., Phys. Rev. C 97, 034917 (2018).
[4] Gao et al., Phys. Rev. D 104, 076016 (2021).
[5] Müller et al., Phys. Rev. D 105, L011901 (2022).
[6] Xia et al., Phys. Lett. B 817, 136325 (2021).
[7] Sheng et al., Phys. Rev. D 102, 056013 (2020).

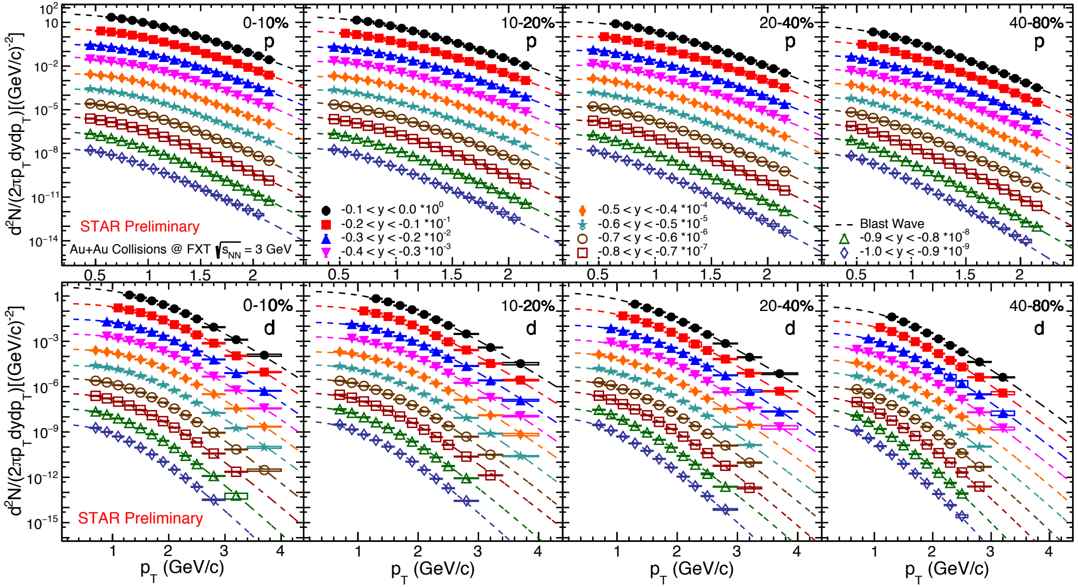
Deuteron Number Fluctuation

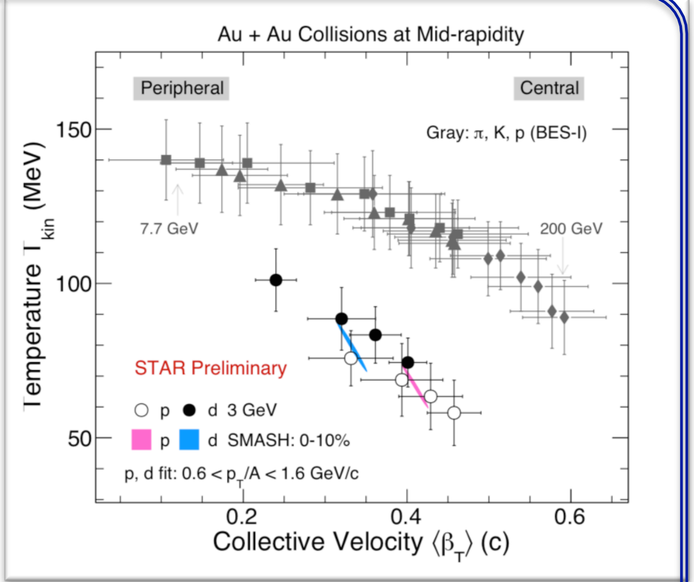
Difference with net-proton:
Different freeze out

Smooth energy dependence of C_4/C_2



Kinetic Freeze-out at 3 GeV





- Kinetic freeze-out parameters extracted using cylindrical blast-wave model
- Kinetic freeze-out temperature at 3 GeV is lower than other higher energies
- T_{kin}(deuteron) > T_{kin} (proton)